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Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses

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Abstract

Mechanical properties of wheat straw, barley straw, corn stover and switchgrass were determined at different compressive forces, particle sizes and moisture contents. Ground biomass samples were compressed with five levels of compressive forces (1000, 2000, 3000, 4000 and 4400 N) and three levels of particle sizes (3.2, 1.6 and 0.8 mm) at two levels of moisture contents (12% and 15% (wet basis)) to establish compression and relaxation data. Compressed sample dimensions and mass were measured to calculate pellet density. Corn stover produced the highest pellet density at low pressure during compression. Compressive force, particle size and moisture content significantly affected the pellet density of barley straw, corn stover and switchgrass. However, different particle sizes of wheat straw did not produce any significant difference on pellet density. The relaxation data were analyzed to determine the asymptotic modulus of biomass pellets. Barley straw had the highest asymptotic modulus among all biomass indicating that pellets made from barley straw were more rigid than those of other pellets. Asymptotic modulus increased linearly with an increase in compressive pressure. A simple linear model was developed to relate asymptotic modulus and maximum compressive pressure.

Keywords: Wheat straw; Barley straw; Corn stover; Switchgrass; Physical properties; Pellet density and Asymptotic modulus

1. Introduction

Cereal straws and corn stover are abundantly available in the US and Canada. Switchgrass (*Panicum virgatum* L.) is viewed as a major future dedicated energy crop. One of the major barriers against the use of these bulky residues as feedstocks is on their collection, handling, transportation and storage. The bulk density of loose straw is around $40\,kg\,m^{-3}$, whereas the highest bulk density of unprocessed wood residue is around $250\,kg\,m^{-3}$ [1,2]. Therefore, these bulky residues can be densified into pellets. Pelletizing is a method of increasing the bulk density of biomass by mechanical pressure. Pellets have low moisture content (about 8% wet basis (wb)) for safe storage and a high bulk density (more than $600\,kg\,m^{-3}$) for efficient transport and storage. Biomass pellets that are usually 6–8 mm in diameter and 12–15 mm long flow with gravity. They can be handled, transported and fed to boilers and furnaces easily. The process of forming biomass into pellets depends upon the physical properties of ground particles and the process variables during pelletizing, i.e. pressure and temperature.

The compaction (pelletization) process is a complex interaction between particles, their constituents and forces. Mani et al. [3] evaluated the compaction mechanism of straws, stover and switchgrass using different compaction models. Mani et al. [4] and Samson et al. [5] reviewed the biomass pelleting process and the effect of various process parameters on pellet density and durability. Tabil and Sokhansanj [6] studied the bulk properties of alfalfa in relation to its compaction characteristics. They reported that pellets from high-quality alfalfa chops were more compressible (higher density) than pellets from low-quality chops. The contributed difference in density was due to higher leaf content and thus protein content of high-quality

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alfalfa chops. Samson et al. [7] and Jannasch et al. [8] reported the energy analysis and assessment of switchgrass pelleting process. They found that switchgrass pellet hardness moderately increased with a decrease in particle screen size from 3.2 to 2.8 mm.

Knowledge of the fundamental compaction properties of particles of different biomass species, sizes, shapes, chemical compositions, bulk densities and particle densities is essential to optimize densification processes [9–11]. It is also important to understand the compaction mechanisms in order to design energy-efficient compaction equipment and to quantify the effects of various process variables on pellet density and pellet durability.

The objective of this study was to investigate the effects of compressive force, particle size and moisture content on the mechanical properties of wheat and barley straws, corn stover and switchgrass.

2. Materials and methods

2.1. Crop residues

Wheat (*Triticum spp.*) and barley (*Hordeum vulgare*) straws (unknown variety) in square bales were obtained from an experimental farm near Saskatoon, Saskatchewan, Canada. The bales were of dimensions of $0.45 \times 0.35 \times 1.00$ m with moisture contents of 8.3% (wb) for wheat and 6.9% (wb) for barley. Corn stover was collected in the form of whole plant without cobs from a sweet corn variety grown in Saskatoon. The average stover moisture content was 6.2% (wb). The straws and corn stover were harvested in October 2001 and stored for 8 months in a covered shed. Switchgrass var 'Pathfinder' was received from Montreal, Quebec, Canada. Its moisture content was 5.2% (wb). Switchgrass was harvested in April 2002 and was stored for a month in the lab.

2.2. Material preparation

Biomass samples were ground using a hammer mill (Glen Mills Inc., NJ) with three different hammer mill screen sizes (3.2, 1.6 and 0.8 mm). The samples were wetted by sprinkling water on them to moisture contents of 12% and 15% (wb) and stored in a cooler kept at 4 °C for a minimum of 72 h.

2.3. Chemical composition

Biomass samples were analyzed by a commercial animal feed testing laboratory in Saskatoon (Enviro-test Laboratory, Saskatoon, SK). Protein, crude fat, acid detergent lignin (ADL), acid detergent fiber (ADF), neutral detergent fiber (NDF) and total ash were determined. The protein content of the biomass was determined using the AOAC method 976.06 [12], where the nitrogen content was multiplied by a factor 6.25. Crude fat was determined using the AOAC method 920.29 [13]. ADF and ADL were determined using the AOAC method 973.18 [14], whereas the NDF was determined using the method reported by van Soest et al. [15]. The total ash content was determined using AOAC method 942.05 [16].

2.4. Particle size analysis

A sample of 100 g was placed in a stack of sieves arranged from the largest to the smallest opening. The sieve series selected were based on the range of particles in the sample. For the samples from 3.2 mm hammer mill screen opening, Canadian series sieve numbers 10, 14, 16, 18, 20, 30, 40, 50, 70, 100, 140 and 200 (sieve sizes: 2.0, 1.4, 1.2, 1.0, 0.85, 0.59, 0.43, 0.30, 0.21, 0.15, 0.11 and 0.075 mm, respectively) were used. For samples from 1.6 mm hammer mill screen opening, sieve numbers 20, 30, 40, 50, 70 and 100 (0.85, 0.59, 0.43, 0.30, 0.21 and 0.15 mm, respectively) were used. For the finely ground samples from 0.8 mm hammer mill screen opening, sieve numbers 30, 40, 50, 70, 100 and 140 (0.59, 0.43, 0.30, 0.21, 0.15 and 0.11 mm, respectively) were used. The set of sieves was placed on the Ro-Tap sieve shaker (Tyler Industrial Products, OH). The duration of sieving was 10 min, which was previously determined through trials to be optimal. This time duration was sufficient for straw samples, because of their fluffy and fibrous nature. After sieving, the mass retained on each sieve was weighed. Sieve analysis was repeated three times for each ground sample. The particle size was determined according to ANSI/ASAE standard S319.3 JUL 97 [17]. The geometric mean diameter (d_{gw}) of the sample and geometric standard deviation of particle diameter (S_{gw}) were calculated according to the aforementioned standard.

2.5. Moisture content

The moisture content of the ground samples was determined following the procedure given in ASTM Standard D 3173-87 for coal and coke [18]. One gram of pulverized sample passing through sieve number 60 was taken and oven-dried for 1 h at 130 °C. The moisture content of the samples was determined by weighing and expressed in percent wb.

2.6. Bulk density and particle density

Bulk density of ground samples was measured using the grain bulk density apparatus. The sample was placed on the funnel and dropped at the center of a 0.5 L steel cup continuously. Since the sample was fluffy and did not flow down readily through the funnel, it was stirred using a thin rod in order to maintain a continuous flow of the material. The cup was leveled gently by a rubber-coated steel rod and weighed. Mass per unit volume gave the bulk density of the biomass in kg m^{-3}. Particle density of the sample was measured by a method adopted by Mani et al. [19].

2.7. Compression test

Compression test was conducted using a single pelleter unit [7] for four biomass samples from three different hammer mill screen sizes (3.2, 1.6 and 0.8 mm) at 12% (wb) and 15% (wb) moisture content. A known amount (0.2–0.4 g) of biomass sample was compacted in the single pelleter unit. The die was heated to 100 °C in order to simulate the heating during commercial compacting process for alfalfa. Compression of the ground sample was performed by the Instron testing machine (Instron Corp., Canton, MA) fitted with a 5000 N load cell and a 6.4 mm plunger. The preset loads used for the test were 1000, 2000, 3000, 4000 and 4400 N at a crosshead speed of 50 mm min^{-1}. The sample was fed into the heated die and compressed up to the specified preset load and held for 60 s to arrest the spring back effect. The force–deformation data during compression and the force–time data during stress relaxation were logged in the computer. The pellet formed was removed by gentle tapping using a plunger. The mass, length and diameter of the pellet were measured. Each compression test was repeated five times.

2.8. Pellet density

The effects of force applied, screen size and moisture content on pellet density of wheat and barley straws, corn stover and switchgrass were analyzed using Statistical Analysis Systems (SAS) software [20] by Duncan multiple range tests.

2.9. Residual modulus after relaxation

The relaxation data for each biomass sample were analyzed by the method of Peleg [21], which was applied to powders by Peleg and Moreyra [22] and to alfalfa powders by Tabil and Sokhansanj [6]. The force relaxation curves of biomass pellet were normalized and linearized and represented as straight line in the form of [23]:

$$\frac{\sigma_0 t}{\sigma_0 - \sigma(t)} = k_1 + k_2 t, \tag{1}$$

where σ_0 is the initial stress (MPa), $\sigma(t)$ the stress after time t at relaxation (MPa), t the time (s) and k_1, k_2 are the empirical constants.

The slope k_2 of the straight line must be greater than one, and from a rheological point of view, the slope can be considered as an index of how solid the compacted specimen is on a short time scale. Any large value of greater than one is an indication of the existence of stresses that will eventually remain unrelaxed [24].

Moreyra and Peleg [24] and Scoville and Peleg [25] stated that the asymptotic modulus (E_A) can be an empirical index of solidity which is the ability of the compressed powder to sustain unrelaxed stresses; E_A is defined as

$$E_A = \frac{\sigma_0}{\varepsilon}\left(1 - \frac{1}{k_2}\right) \tag{2}$$

where E_A is the asymptotic modulus (MPa) and ε is the strain (dimensionless or m m^{-1}).

Eq. (1) was fitted to the stress relaxation data to estimate k_1 and k_2. The estimated k_2 value was used in Eq. (2) to calculate E_A for each sample.

3. Results and discussions

3.1. Chemical composition

The chemical composition of four biomass species tested for mechanical properties is presented in Table 1. The chemical compositions of wheat and barley straws are almost identical except for ash content. Ash content of barley straw (10.7%) was higher than wheat straw (8.3%). Among chemical components, the presence of protein and lignin may enhance the pelleting property of biomass powders. The presence of lignin in feed material enhances the binding characteristics of densified pellets during the preheating of the material. Lignin has a low melting point of about 140 °C. When biomass is heated, lignin becomes soft and sometimes melts and exhibits thermosetting properties [26]. Protein also plays a major role as a binding agent between different particles during compaction. During densification, the material experiences the combined effect of shear, heat, residence time and water resulting in partial denaturation of protein in the biomass [27]. Wood [28] reported that partial denaturation during processing may positively affect the hardness and durability of the pellets. Upon cooling, the protein

Table 1
Chemical composition of biomass species

Components	Biomass species			
	Wheat straw	Barley straw	Corn stover	Switchgrass
Protein, % DM[a]	5.70	6.60	8.70	1.59
Crude fat, % DM	1.61	1.33	1.33	1.87
Lignin, % DM	7.61	6.81	3.12	7.43
Cellulose[b], % DM	42.51	42.42	31.32	44.34
Hemi-cellulose[c], % DM	22.96	27.81	21.08	30.00
Ash, % DM	8.32	10.72	7.46	5.49

[a]DM—dry matter.

[b]Cellulose percentage is calculated indirectly from acid detergent fiber (ADF) and lignin (ADF–lignin).

[c]Hemi-cellulose percentage is also calculated indirectly from neutral detergent fiber (NDF) and ADF (NDF–ADF).

reassociates and bonds can be established between different particles. However, these behaviors were not examined in this study.

3.2. Physical properties

Table 2 shows the geometric mean diameter, bulk density and particle density of four biomass species. For the same hammer mill screen size, the geometric mean particle diameter of wheat straw sample was slightly smaller than that of barley straw sample. This might be due to the variation in moisture content of straw materials as well as difference in mechanical properties of wheat and barley straws. The corn stover sample was the finest among the four biomass samples. Bulk density and particle density of ground biomass from different hammer mill screen sizes are given in Table 2. It can be observed that the larger the screen openings, the lower were the bulk and particle densities. Bulk and particle densities of ground wheat straw were slightly higher than that of barley straw sample. Ground switchgrass from a hammer mill screen size of 0.8 mm had the highest bulk density of 181.56 kg m^{-3}. Among all four biomass samples, ground corn stover had the highest bulk density and particle density due to the smallest geometric mean particle diameter it had for hammer mill screen sizes of 3.2 and 1.6 mm.

3.3. Pellet density

The effect of compressive pressure on the pellet density of wheat and barley straws, corn stover and switchgrass ground with 3.2 mm hammer mill screen size and 12% (wb) moisture content is shown in Fig. 1. For all biomass samples, as compressive load increased, the density of the pellet approached close to the particle density value of the sample. But in the case of corn stover, the density of the pellet reached magnitudes close to the particle density value even at low pressures, which showed that ground corn stover could be easily compressed at low pressures. High protein content in the corn stover could also lead to high pellet density at low pressure as protein melts at high temperature and acts as a binder during compression as discussed earlier. Pellet density of the biomass samples slightly increased as the hammer mill screen size decreased except for wheat straw samples (data not shown). Variations observed in the compression data may be due to variations in pellet dimensions and mass and the inherent variability of the sample itself.

The effects of compressive force, screen size and moisture content on pellet density were analyzed using SAS by analysis of variance (ANOVA) and Duncan multiple range tests. Table 3 shows the ANOVA of factors affecting the biomass pellet density. Compressive force (f), screen size (s) and moisture content (m) significantly affected pellet density ($P = 0.05$). Although hammer mill screen sizes (3.2, 1.6 and 0.8 mm) did not have significant

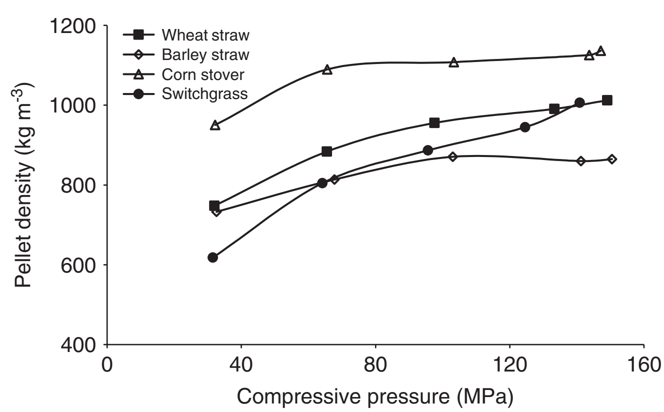

Fig. 1. Relationship between compressive pressure and pellet density of four biomass samples from 3.2 mm screen size with 12% (wb) moisture content.

Table 2
Physical properties of four biomass species

Material	Moisture content (%, wb)	Hammer mill screen size (mm)	Geometric mean diameter (mm)	Geometric standard deviation (mm)	Bulk density (kg m^{-3})	Particle density (kg m^{-3})
Wheat straw	8.30	3.2	0.639	0.306	97.37 (0.78)*	1026.57 (6.39)*
		1.6	0.342	0.196	106.73 (1.02)	1258.45 (7.91)
		0.8	0.281	0.201	121.29 (1.32)	1344.07 (1.92)
Barley straw	6.98	3.2	0.691	0.364	80.99 (0.71)	887.34 (6.57)
		1.6	0.383	0.222	101.44 (0.50)	1178.05 (6.69)
		0.8	0.315	0.217	112.13 (0.74)	1245.36 (7.51)
Corn stover	6.22	3.2	0.412	0.261	131.37 (2.25)	1169.91 (4.54)
		1.6	0.262	0.447	155.64 (2.15)	1330.78 (4.24)
		0.8	0.193	0.308	157.73 (1.54)	1399.16 (3.89)
Switchgrass	8.00	3.2	0.456	0.255	115.4 (1.31)	945.97 (4.60)
		1.6	0.283	0.391	156.20 (1.99)	1142.36 (4.79)
		0.8	0.253	0.438	181.56 (1.17)	1172.75 (2.71)

*Number enclosed in parenthesis are standard deviations for $n = 5$.

Table 3
Analysis of variance (ANOVA) table for factors affecting density of biomass pellets

Source variables	Sum of squares	Df*	Mean square	*F* value	Probability
Wheat straw					
Force (*f*)	741 910	4	185 478	440.4	0.00
Particle size (*s*)	2018	2	1009	2.4	0.10
Moisture content (*m*)	253 239	1	253 239	601.3	0.00
$s \times m$	18 204	2	9102	21.6	0.00
$f \times s$	67 876	8	8485	20.1	0.00
$f \times m$	29 840	4	7460	17.7	0.00
$f \times s \times m$	53 297	8	6662	15.8	0.00
Error	50 541	120	421		
Barley straw					
Force (*f*)	867 234	4	216 809	708.8	0.00
Particle size (*s*)	169 005	2	84503	276.2	0.00
Moisture content (*m*)	360 171	1	360 171	1177.4	0.00
$s \times m$	86 535	2	43267	141.4	0.00
$f \times s$	75 631	8	9454	30.9	0.00
$f \times m$	42 135	4	10 534	34.4	0.00
$f \times s \times m$	27 205	8	3401	11.12	0.00
Error	36 708	120	306		
Corn stover					
Force (*f*)	1 287 517	4	321 879	522.6	0.00
Particle size (*s*)	195 632	2	97 816	158.8	0.00
Moisture content (*m*)	62 040	1	62 040	100.7	0.00
$s \times m$	2927	2	1464	2.4	0.01
$f \times s$	22 048	8	2756	4.5	0.00
$f \times m$	41 819	4	10 455	17.0	0.00
$f \times s \times m$	6076	8	760	1.23	0.29
Error	73 910	120	616		
Switchgrass					
Force (*f*)	1 630048	4	407 512	987.4	0.00
Particle size (*s*)	15 550	2	7775	18.8	0.00
Moisture content (*m*)	156 262	1	156 262	378.6	0.00
$s \times m$	44 939	2	22 469	54.4	0.00
$f \times s$	83 772	8	10 472	25.37	0.00
$f \times m$	9059	4	2265	5.5	0.00
$f \times s \times m$	18 513	8	2314	5.6	0.00
Error	49 525	120	413		

*df = degree of freedom.

effect on pellet density produced from ground wheat straw sample, the interactions of screen size with other two factors ($s \times f$, $s \times m$) were significant. This may be due to the stiffness of particles and different elastic properties of wheat straw, which make the particles rigid to compression pressure. The interaction of three factors ($f \times s \times m$) did not significantly affect the density of corn stover pellets.

Moisture content of ground biomass also significantly affected the pellet density. In general, as moisture content of biomass increased, pellet density decreased. Gustafson and Kjelgaard [29] studied the compaction of hay for a wide range of moisture (28–44% (wb)) and found that the density of the product decreased as moisture content increased. Rehkugler and Buchele [30] reported that there was a reduction in relaxed density of pellet for moisture content ranging between 6% and 25% (wb).

3.4. Asymptotic modulus

Fig. 2 shows a typical force–time relationship showing the deformation and relaxation phases during compression. In some tests, especially at 4400 N preset load, the asymptotic modulus was not calculated due to the nonavailability of relaxation data. The data logger stopped recording the data when the load exerted on the plunger exceeded 5000 N which happened when the load was preset at 4400 N. This was due to the rapid movement of the crosshead of the Instron testing machine. As a result, the plunger which compressed the sample could not be stopped instantaneously at 4400 N and the maximum load of 5000 N on the plunger exceeded the preset load.

Fig. 3 shows typical stress relaxation and linearized curves for wheat straw sample at 12% moisture content. Stress relaxation data for each biomass sample were linearized and fitted with Eq. (1). The slope of the line, k_2, is called as the solidity index of the material. The value of k_2 was used to determine the asymptotic (relaxation) modulus of the material. Asymptotic modulus is defined as

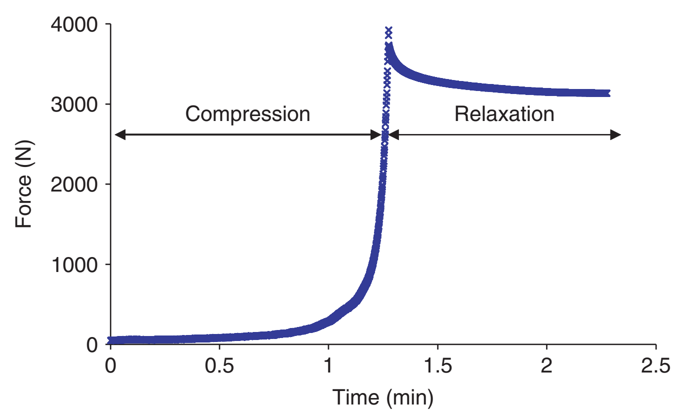

Fig. 2. Typical compression and relaxation curve of a biomass sample (wheat straw).

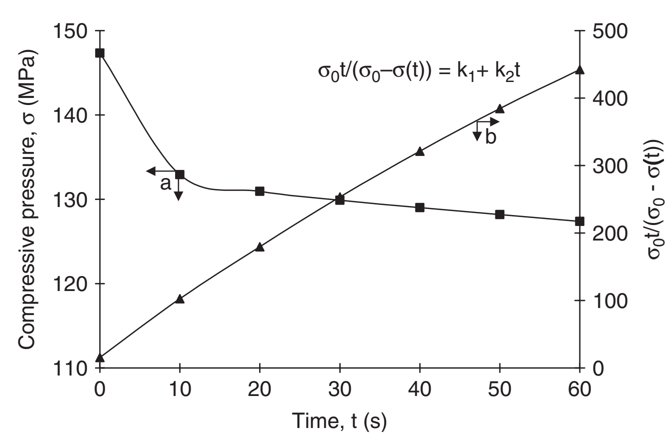

Fig. 3. Typical relaxation and linearization curves of biomass sample (wheat straw) from 3.2 mm screen size with 12% (wb) moisture content; (a) stress relaxation curve and (b) linearization curve.

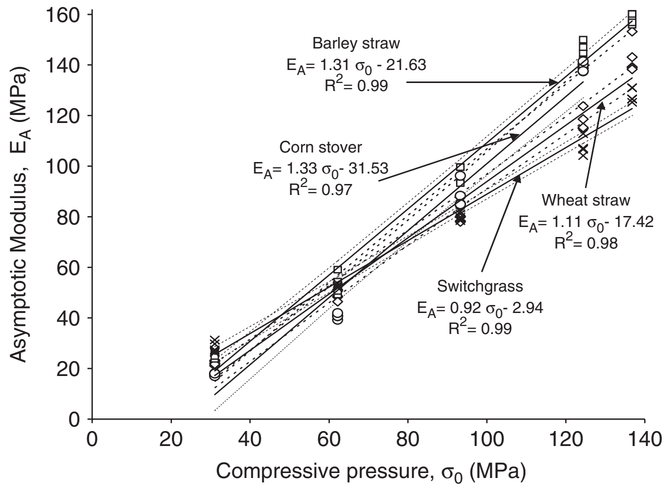

Fig. 4. Relationship between compressive pressure and asymptotic modulus of compressed biomass samples from 3.2 mm screen size at a moisture content of 12% (wb).

the ability of the compressed powder to sustain unrelaxed stresses, i.e., it is an indication of the pellet solidity since it reflects the stresses that can be supported without dissipation through plastic flow of the solid matrix and reorientation of the interparticle bridges [24]. The ground barley straw sample had the highest asymptotic modulus among the four biomass samples indicating that this pellet sample was more rigid than other pellets. Therefore, it can be concluded that the asymptotic modulus can also be used to characterize different biomass samples. Fig. 4 shows a typical relationship between the compressive pressure and asymptotic modulus. The increase in asymptotic modulus (E_A) with the maximum compressive pressure (σ_0) was fitted to a linear model. The model fitted well to the data for all four biomass species with higher R^2 values. The 95% confidence bounds (dotted lines) for the linear models (solid lines) showed the statistical significance of the developed models. Tabil and Sokhansanj [6] showed the relationship between the asymptotic modulus and compressive pressure using a power model for alfalfa. It is shown in Fig. 4 that barley straw produced more rigid pellet followed by corn stover, wheat straw and switchgrass.

4. Conclusions

The present work examined the effects of compressive force, particle size and moisture content on the mechanical properties of biomass pellets. It was found that all these variables significantly affected pellet density except no significant effect was observed for particle size on the pellet density of wheat straw. Corn stover sample produced the highest pellet density of 1136 kg m^{-3} from 3.2 mm hammer mill screen size at 12% moisture content. A linear model was developed to determine the effect of maximum compressive pressure on the asymptotic modulus. Among the four biomass species, barley straw pellets had the highest asymptotic modulus.

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